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Comparison of shooting arm motions in basketball

Hiroki Okubo[a], Mont Hubbard[b]

[a]Chiba Institute of Technology, 2-17-1 Tsudanuma Narashino, Chiba 2750016, Japan
[b]University of California, Davis, CA 95616, USA

Abstract

A kinematic model is used to analyze basketball shooting arm motions in the vertical plane that produce desired ball release speed, angle and backspin. The release conditions are related to arm motions using general kinematic equations. The paper compares three types of shooting arm motions: pure hand shots, hand-forearm shots, and general shots controlled by hand, forearm and upper arm motions. In pure hand shots, release speed, angle and backspin are severely limited. All hand-forearm shot configurations are able to produce desired release speed, angle and backspin. General shots redundantly provide shooters with any desired ball release speed, angle and backspin, and they are required to suitably control each joint angular velocity and acceleration.

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Keywords:
basketball shooting, release speed, release angle, backspin, arm joint motion

1. Introduction

One hand set and jump shots are most commonly used in basketball games. Shooters hold the ball in the shooting hand, place it near their forehead, raise and extend the elbow and snap the wrist forward. The non-shooting hand helps to support the ball and allows release at the desired position. Many players use their upper arm, forearm and hand rotations, but some use mostly their forearms and hands. To avoid blocked shots, they position the ball high and snap their wrists in shooting. In general, different types of shooting arm motions are used for different skill sets and/or court situations.

Some previous basketball studies[1–3] measured shooting arm joint motions. Tsarouchas et al. [4] studied shooting styles and compared a high elbow technique to a lower elbow starting position. They pointed out that the high elbow technique diminished the effect of angular motion at the shoulder, thus simplifying the shooting technique. Okubo and Hubbard [5] have derived the kinematics of the shooting arm motion and showed the angular displacement and velocity combinations of shooters' shoulder, elbow and wrist joints that produce a set of desired release speed, angle and backspin.

* Corresponding author. Tel.: +81-47-478-0186 ; fax: +81-47-478-0186.
E-mail address: hiroki.okubo@it-chiba.ac.jp

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Our research goal is to study more comprehensively the dependence of shooters' desired release conditions on the corresponding arm motions. No dynamic model has been used to compare different types of shooting arm motions. We add kinetic constraints of the basketball at release to the kinematic model [5], and analyze three types of shooting arm motion for jump shots with low elbow, high elbow and high wrist starting positions.

2. Analysis of shooting arm motion

2.1. Types of shooting arm

We analyze three types of shooting arm motions: pure hand, hand-forearm, and general shots. Shooters use different shot techniques depending on the situation. In the pure hand shot, in order to avoid blocked shots, they set the ball above their head and use almost entirely wrist motion to accelerate the ball translationally and angularly, while in hand-forearm shots motion occurs at both the wrist and elbow joints. In general shots, shoulder, elbow and wrist rotations are all used. The ball begins near the forehead with the upper arm nearly horizontal. Shooters then raise and extend their elbow and snap their wrist forward. Tsarouchas et al. [4] measured velocities of the elbow and wrist for the high and low elbow technique (shooters mostly use their forearm and hand in the high elbow technique and use their upper arm, forearm and hand in the low elbow technique) in free throws. They concluded that in the high elbow technique the influence of arm movement was small and not as complex as in the low elbow technique. They did not mention the effectiveness of the techniques for high percentage successful shots.

2.2. Model of shooting arm with a basketball

We use a shooting arm model similar to the two dimensional three-segment model of Schwark et al. [6]. The shooting arm is assumed to rotate in the vertical plane and have three rigid links (an upper arm, forearm and hand) with rotational joints at the shoulder, elbow and wrist. A coordinate system is shown in Fig. 1. The Newtonian frame XYZ with unit vectors $\boldsymbol{I}$, $\boldsymbol{J}$, $\boldsymbol{K}$ is fixed relative to the court with the XY plane horizontal and Z axis up. The YZ plane includes the arm links. The ball center moves in this plane after release, and the angular velocity vectors of the ball and arm segments at release are perpendicular to this initial shot path plane. Links U, F, H, and points S, E, W and $\hat{H}$ denote the upper arm, forearm and hand links, and the shoulder, elbow, and wrist joints and fingertip, respectively. Body B and point B^* denote the basketball and the ball center. The lengths of the upper arm, forearm, and hand links and ball radius are L_U, L_F, L_H and R_b, respectively. Arm configuration is defined using counterclockwise angular displacements of the segments from the horizontal plane; Ψ_U, of the upper arm; Ψ_F, of the forearm; Ψ_H, of the hand; and Ψ_B, of a line including the fingertip and ball center.

2.3. Release conditions

The equation of motion of the ball in non-slipping contact with the shooter's fingertip is

$$-mg\boldsymbol{K} + \hat{B}_Y\boldsymbol{J} + \hat{B}_Z\boldsymbol{K} = m(\ddot{y}\boldsymbol{J} + \ddot{z}\boldsymbol{K}) \tag{1}$$

where y and z are the horizontal and vertical components of the ball center B^*, m is ball mass, g is gravity, and $\hat{B}_Y$ and $\hat{B}_Z$ are horizontal and vertical components of the force exerted by the fingertip. When the ball is released, the contact force vanishes and the ball acceleration becomes $\ddot{y} = 0$ and $\ddot{z} = -g$. The horizontal and vertical positions y and z can be written as $y = R_b \cos\Psi_B + y_{\hat{H}}$ and $z = R_b \sin\Psi_B + z_{\hat{H}}$ where $y_{\hat{H}}$ and $z_{\hat{H}}$ are the horizontal and vertical components of the fingertip position. The second time derivatives are $\ddot{y} = -R_b(\ddot{\Psi}_B \sin\Psi_B + \dot{\Psi}_B^2 \cos\Psi_B) + \ddot{y}_{\hat{H}}$ and $\ddot{z} = R_b(\ddot{\Psi}_B \cos\Psi_B - \dot{\Psi}_B^2 \sin\Psi_B) + \ddot{z}_{\hat{H}}$ where $\dot{\Psi}_B$ is the ball angular velocity. Because the ball angular velocity is constant after release, $\ddot{\Psi}_B = 0$. Substituting $\ddot{\Psi}_B = 0$, $\ddot{y} = 0$ and $\ddot{z} = -g$ into the expressions of the angular acceleration gives the horizontal and vertical components of the fingertip acceleration.

$$\begin{aligned} \ddot{y}_{\hat{H}} &= R_b \dot{\Psi}_B^2 \cos\Psi_B \\ \ddot{z}_{\hat{H}} &= R_b \dot{\Psi}_B^2 \sin\Psi_B - g \end{aligned} \tag{2}$$

We assume that shooters release the ball without slipping between the fingertip and the ball surface at the fingertip contact point. The initial ball backspin angular velocity ω equals $\dot{\Psi}_B$. The relationship between ω and $(\ddot{y}_{\hat{H}}, \ddot{z}_{\hat{H}})$

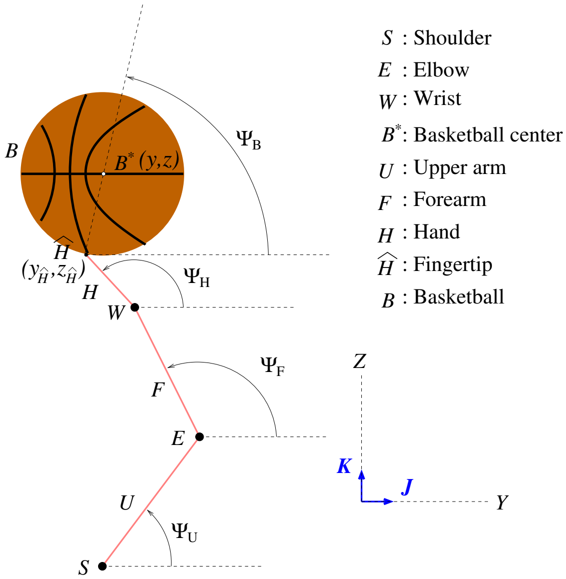

Fig. 1. Geometry of shooting arm with a basketball.

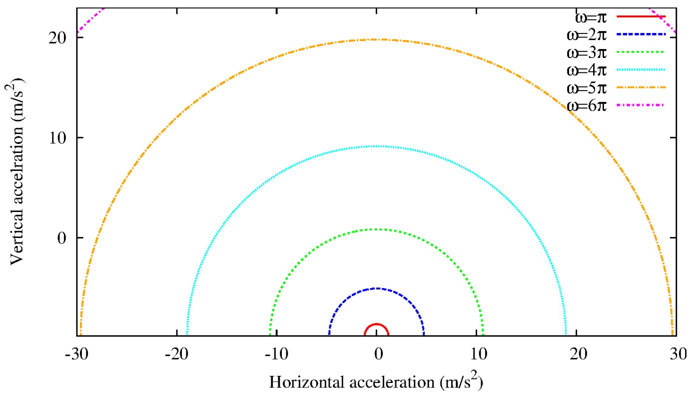

Fig. 2. Backspin angular velocity ω as a function of fingertip acceleration.

becomes $\ddot{y}_{\hat{H}}^2 + (\ddot{z}_{\hat{H}} + g)^2 = (R_b\omega^2)^2$ as depicted in Fig. 2. Heavy backspin requires a large magnitude of total fingertip acceleration.

Fingertip velocity can be written as ${}^N\boldsymbol{v}^{\hat{H}} = {}^N\boldsymbol{v}^{B^*} + \omega \boldsymbol{I} \times \boldsymbol{r}^{\hat{H}/B^*}$ where ${}^N\boldsymbol{v}^{B^*}$ is the ball center velocity, ω is ball angular velocity and $\boldsymbol{r}^{\hat{H}/B^*}$ is the position vector from B^* to $\hat{H}$. When the ball is released with ball speed v, release angle α from the horizontal plane and ball angular velocity ω, the horizontal and vertical components of fingertip velocity can be written as

$$\begin{aligned} \dot{y}_{\hat{H}} &= v\cos\alpha + R_b\omega\sin\Psi_B \\ \dot{z}_{\hat{H}} &= v\sin\alpha - R_b\omega\cos\Psi_B \end{aligned} \tag{3}$$

3. Results and discussion

3.1. Simulation parameters

We analyze three types of jump shots: short-range shots for a 6’11”(211cm) center player, medium-range shots for a 6’7”(201cm) forward player and long-range shots for a 6’3”(191cm) guard player. The horizontal and vertical

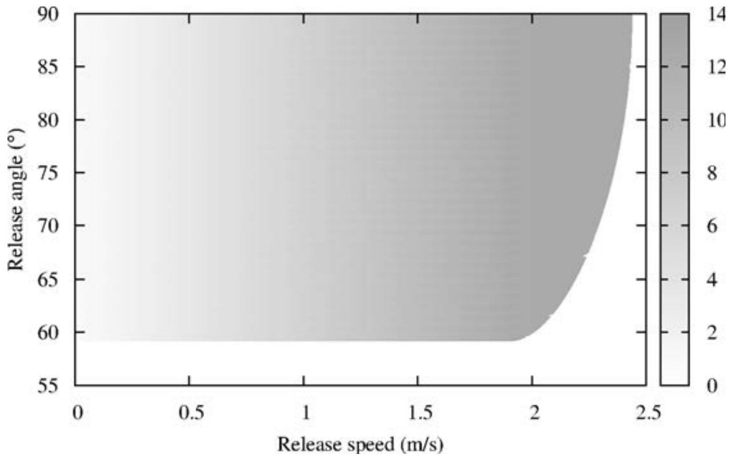

Fig. 3. Possible ball release speed, angle and backspin angular velocity for jump shots with hand shot (high wrist) technique. Darker areas correspond to larger angular velocity.

distances between the hoop center and the ball release point are $l = 2$ m, $h = 0.05$ m for short-range shots, $l = 4$ m, $h = 0.15$ m for medium-range shots and $l = 7$ m, $h = 0.30$ m for long-range shots. The lengths of upper arm L_U, forearm L_F and hand L_H are calculated, using the values of De Leva[7], as $L_U = 0.308$ m, $L_F = 0.294$ m and $L_H = 0.208$ m for the guard, $L_U = 0.325$ m, $L_F = 0.310$ m and $L_H = 0.219$ m for the forward, and $L_U = 0.341$ m, $L_F = 0.326$ m and $L_H = 0.230$ m for the center.

3.2. *Pure hand jump shots*

In all jump shots analyzed below, we assume that ball release occurs at the peak of the jumper's vertical path, where the shooter's body (excluding moving arm segments) has zero velocity and downward acceleration due only to gravity. In pure hand jump shots, a reasonable condition is therefore that the wrist joint velocity and acceleration are ${}^N\boldsymbol{v}^W = 0$ and ${}^N\boldsymbol{a}^W = -g\boldsymbol{K}$ at release. Non-slipping release, in which the ball is released without slipping between the fingertip and the ball surface, gives the kinematic constraint equations

$$\begin{aligned}
v\cos\alpha + R_b\omega\sin\Psi_B &= -L_H\dot{\Psi}_H\sin\Psi_H \\
v\sin\alpha - R_b\omega\cos\Psi_B &= L_H\dot{\Psi}_H\cos\Psi_H \\
R_b\omega^2\cos\Psi_B &= -L_H(\ddot{\Psi}_H\sin\Psi_H + \dot{\Psi}_H^2\cos\Psi_H) \\
R_b\omega^2\sin\Psi_B &= L_H(\ddot{\Psi}_H\cos\Psi_H - \dot{\Psi}_H^2\sin\Psi_H)
\end{aligned} \tag{4}$$

Possible ball release speed, angle and backspin angular velocity can therefore be written as

$$\begin{aligned}
v &= \sqrt{L_H^2\dot{\Psi}_H^2 + R_b^2\omega^2 + 2L_HR_b\omega\cos(\Psi_B - \Psi_H)} \\
\alpha &= \tan^{-1}\left(\frac{L_H\dot{\Psi}_H\cos\Psi_H + R_b\omega\cos\Psi_B}{-L_H\dot{\Psi}_H\sin\Psi_H - R_b\omega\sin\Psi_B}\right) \\
\omega &= \sqrt[4]{\left(\frac{L_H}{R_b}\right)^2(\ddot{\Psi}_H^2 + \dot{\Psi}_H^4)}
\end{aligned} \tag{5}$$

The release conditions are functions of Ψ_H, $\dot{\Psi}_H$, $\ddot{\Psi}_H$ and Ψ_B and are plotted in the range of $0 \le \omega \le 4\pi$ rad/s, $0 < \alpha < \pi/2$, $0 \le \Psi_B \le \pi/2$ and $\pi/2 \le \Psi_H \le \pi$ for the center player in Fig. 3. The colored regions show possible release combinations of release speed and angle, and the intensity of color shows the corresponding backspin angular velocity. As release speed increases, backspin also increases. However, it is not possible to produce a release angle less than about 59°.

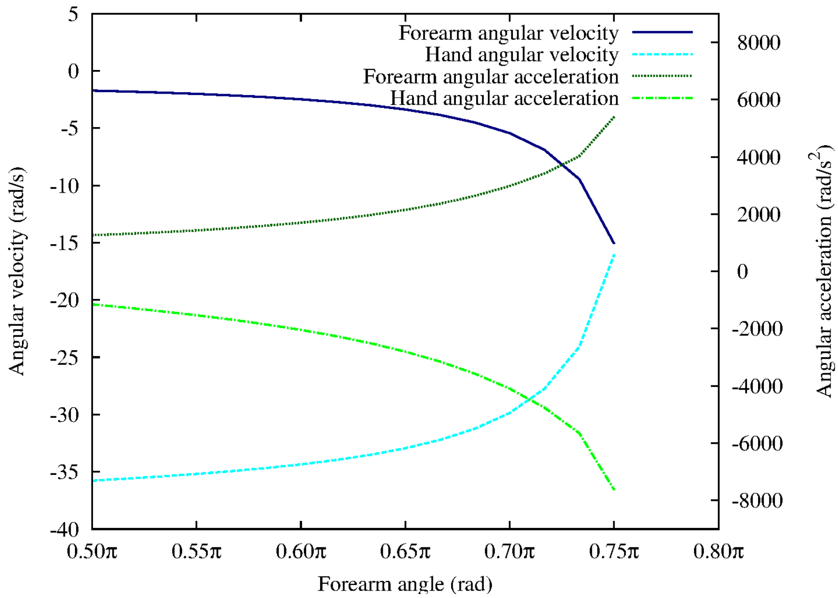

Fig. 4. Elbow and wrist angular velocity and acceleration for the forward player to produce $v = 6.68$ m/s, $\alpha = 46.5°$ and $\omega = 4\pi$ with hand-forearm (high elbow) technique.

3.3. Hand-forearm jump shots

In hand-forearm jump shots, the release condition is that the elbow joint velocity and acceleration are, respectively, ${}^N\boldsymbol{v}^E = 0$ and ${}^N\boldsymbol{a}^E = -g\boldsymbol{K}$. The non-slipping release assumption leads to the kinematic constraint equations

$$\begin{aligned} v\cos\alpha + R_b\omega\sin\Psi_B &= -L_F\dot{\Psi}_F\sin\Psi_F - L_H\dot{\Psi}_H\sin\Psi_H \\ v\sin\alpha - R_b\omega\cos\Psi_B &= L_F\dot{\Psi}_F\cos\Psi_F + L_H\dot{\Psi}_H\cos\Psi_H \\ R_b\omega^2\cos\Psi_B &= -L_F(\ddot{\Psi}_F\sin\Psi_F + \dot{\Psi}_F^2\cos\Psi_F) - L_H(\ddot{\Psi}_H\sin\Psi_H + \dot{\Psi}_H^2\cos\Psi_H) \\ R_b\omega^2\sin\Psi_B &= L_F(\ddot{\Psi}_F\cos\Psi_F - \dot{\Psi}_F^2\sin\Psi_F) + L_H(\ddot{\Psi}_H\cos\Psi_H - \dot{\Psi}_H^2\sin\Psi_H) \end{aligned} \tag{6}$$

Each shooting arm configuration at release has a set of release conditions v, α and ω. When $\Psi_H = \Psi_B$, v, α, and ω are given, a set of $\dot{\Psi}_F$, $\ddot{\Psi}_F$, $\dot{\Psi}_H$ and $\ddot{\Psi}_H$ can be calculated. We calculate the forearm and hand angular velocities and accelerations of the forward player to produce the release conditions of $v = 6.68$ m/s, $\alpha = 46.5°$ and $\omega = 4\pi$ rad/s when $\Psi_H = 140°$ at release. Some previous studies [1, 2] measured arm joint angles and showed the hand link was in a straight line including the ball center at release. Figure 4 shows the forearm and hand angular velocities and accelerations as a function of the forearm angle Ψ_F at release. Each configuration of shooting arm for this type of shot requires different forearm and hand angular velocities and accelerations at release. The directions of the forearm and the hand angular accelerations are opposite. When the forearm is close to vertical at release, a large magnitude of hand angular velocity is required and the magnitude of forearm angular velocity is small.

3.4. General shots

Okubo and Hubbard [5] have pointed out that there are many arm joint angular displacement and velocity combinations to produce a desired ball release speed, angle and backspin and that each configuration of the shooting arm at release corresponds to a straight line in the the shoulder-elbow-wrist angular velocity space. Fingertip acceleration is a function of angular displacements, velocities and accelerations of the upper arm, forearm and hand in the general shot. The constrained release conditions produce a straight line in the upper arm-forearm-hand angular acceleration space as a function of Ψ_U, $\dot{\Psi}_U$, Ψ_F, $\dot{\Psi}_F$, Ψ_H, and $\dot{\Psi}_H$. Figure 5 shows only one example of the release angular acceleration combinations of the upper arm, forearm and hand for long-range shots of the guard player. The straight line of ω_F, ω_H shows the relationship between the angular velocities of forearm and hand when the forearm and hand are vertical

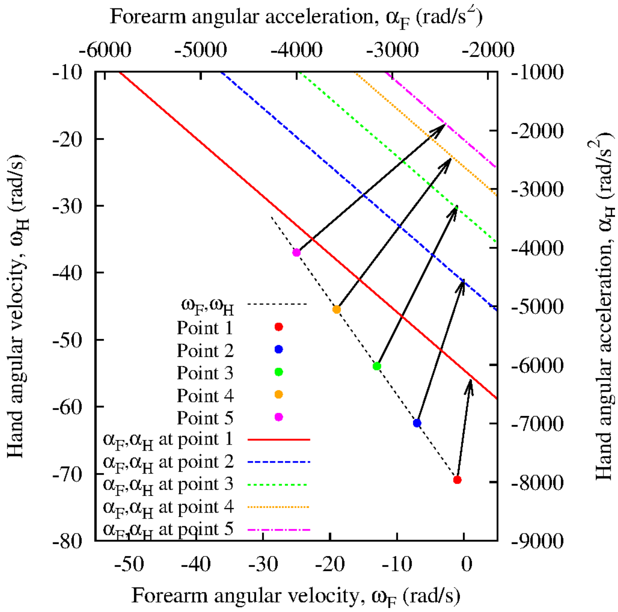

Fig. 5. Numerous richness release combinations of forearm and hand angular accelerations for the general shot. This figure shows only one example of long-range shots when the forearm and hand are vertical at release and $\dot{\Psi}_U = \omega_U = 29.86$ rad/s. Points 1-5 on the straight line of angular velocities ω_F,ω_H have different requirements of angular accelerations of the forearm and hand.

at release. Each point on the ω_F, ω_H line has a set of arm joint angular accelerations. Shooters have numerous choices of arm joint angular velocities and accelerations in the general shot.

4. Conclusions

We have calculated shooting arm motions to produce desired ball release speed, angle and backspin. Backspin angular velocity is a function of the acceleration of the shooting hand fingertip. Heavy backspin requires a large magnitude of fingertip acceleration. We have compared three types of shooting motions: pure hand, hand-forearm, and general shots. In the pure hand jump shot, release combinations in the release speed-angle-backspin space are limited. In the hand-forearm jump shot, each configuration of the shooting arm is able to produce the desired ball release speed, angle and backspin. The general jump shot gives players unlimited release conditions but they are required to control and coordinate correctly all of the upper arm, forearm and hand segments.

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